

Effects of Long-term Exposure to the Low-Earth Orbit Environment on Drag Augmentation Systems

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Abstract

Spacecraft in low-Earth orbit are exposed to environmental threats which can lead to material degradation and component failures. The presence of atomic oxygen and collisions from orbital debris have detrimental effects on the structures, thus affecting their performance. Cranfield University has developed a family of drag augmentation systems (DAS), for end-of-life de-orbit of satellites, addressing the space debris challenge and ensuring that satellites operate responsibly and sustainably. De-orbit devices are stowed on-orbit for the duration of the mission lifetime and, once deployed, the devices must withstand the harsh low Earth environment until re-entry; a process which can take several years. The DAS' deployable aluminised Kapton sails are particularly susceptible to undercutting by atomic oxygen. In preparation for commercialising the DAS, Cranfield University are investigating the degradation process of the drag sail materials, with the end goal of qualifying the materials for the specific application of drag sails in low Earth orbit (LEO). This paper will outline the proposed research and the expected benefits from the projects. This paper will conclude in a summation of the different on-going research projects at Cranfield University related to commercialising the DAS family. This research will benefit the wider space community by expanding the understanding of the effects of long-term exposure on certain materials, as well as improving the validity of future low Earth atmospheric models.

Keywords: Space Debris, Drag Sails, Low Earth Orbit, Material Degradation, Aluminised Kapton, Atomic Oxygen Undercutting

1. Introduction

Space debris is recognised as a critical threat for the space industry. ESA's Annual Space Environment Report [1] provides a detailed assessment of the concerning evolution of the space debris environment, highlighting that as of the end of 2019, approximately 14,000 trackable objects (objects with a diameter ≥ 10 cm [2]) were orbiting Earth in low Earth orbit (LEO).

The number of objects and their combined mass have been steadily rising since the beginning of the space age, leading to involuntary collisions between operational payloads and space debris. Due to their high impact velocity, even small particles can cause significant damage to operational spacecraft. Space users are increasingly aware of the threat of the Kessler syndrome; a potential future scenario where each collision in LEO generates space debris which further increases the likelihood of subsequent collisions.

Simultaneously, the proliferation of small satellites has invited commercialisation and subsequently, the growing number of satellites are adding to the already high number of objects currently in LEO [3]. Small satellites without on-board propulsion have a higher risk of collision since they cannot perform collision avoidance manoeuvres. Low-cost small satellites are under increasing pressure to meet debris mitigation guidelines, which includes post-mission disposal from LEO within 25 years of end of mission [4], and failure to comply could result in a launch licence being denied.

This challenge has encouraged the development of technologies to enable small satellites to operate without causing further debris. Amongst these technologies, drag sails have emerged as a practical, low-cost solution to allow small satellites to comply with regulations and operate sustainably by accelerating the de-orbit process, assisting in the conservation of the space environment. Drag augmentation systems increase the drag area of a

spacecraft at end of mission, minimising the de-orbit period and thus reducing the probability of significant collisions.

Within the framework of ESA's Clean Space initiative CleanSat [5], Cranfield University took part in the technology assessment and concurrent engineering phase, focusing on three key areas: design for demise, de-orbiting systems and passivation. Several of the consolidated requirements from the initiative would require verification to qualify a drag augmentation system. Of these requirements, the ones related to the system lifetime and environment will be difficult to verify due to the complex LEO environment:

- *Lifetime:* The device design shall be compatible with 10 years ground storage, without need for complementary re-acceptance testing at the end of the storage period.
- *Lifetime:* The device shall be able to deploy successfully after a host satellite operational period of up to 10 years in LEO.
- *Environment:* The device shall ensure the expected performance under the radiation conditions observed during the operational lifetime and the disposal phase.
- *Environment:* The device shall ensure the expected performance under the atomic oxygen environment of a worst-case of de-orbit from 600 km, within 25 years from end of mission to re-entry.
- *Environment:* The device shall ensure the expected performance under the debris/meteoroid environment of a worst-case of de-orbit from 800 km, within 25 years from end of mission to re-entry.

Not only would the device have to be compliant with 20 years of storage (both on-ground and in-orbit) before sail deployment, but post sail deployment, the expected performance would need to be ensured for a worst-case de-orbit scenario. This highlights the need to understand the long-term degradation of the drag sail materials in LEO. The sails will be exposed to a harsh environment with accelerated degradation from a combination of atomic oxygen, ultraviolet radiation, thermal cycling, and micrometeoroid and debris bombardment.

This paper will highlight the on-going research at Cranfield University in preparation for commercialising a family of drag sails. Commercialising the systems involves the following three key steps:

1. Assessing and mitigating the key risks associated with the devices.
2. Qualifying the materials in line with the lifetime and environmental requirements.
3. Prototyping and qualifying a new, more scalable and adaptable, drag sail design.

1.1 Cranfield University's Drag Augmentation Systems (DAS) Family

In response to the growing number of small satellites unable to de-orbit from low-Earth orbit within 25 years, Cranfield University has developed a family of drag augmentation systems (DAS) [6]. The DAS are lightweight, cost-effective sails deployed at end of mission and are reliable solutions for de-orbiting small satellites, assisting in the conservation of the space environment. To date, Cranfield has developed and qualified two drag-augmentation system designs: Icarus and De-Orbit Mechanism (DOM), see Fig. 1 and Fig. 2.

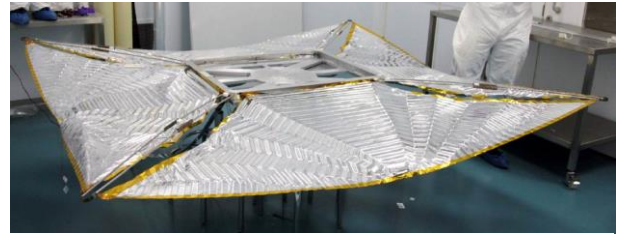


Fig. 1. Icarus-1 in Cleanroom at Cranfield University

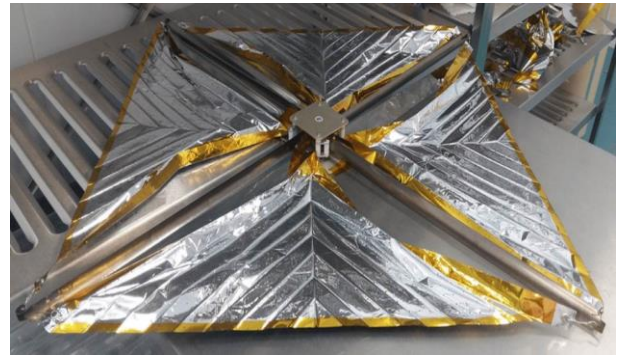


Fig. 2. DOM Flight Model at Cranfield University

Two models of Icarus are currently in orbit (Icarus-1 launched on TechDemoSat-1 in 2014, Icarus-3 launched on Carbonite-1 in 2015) and both have successfully deployed their sails. The DOM was launched on ESA's microsatellite ESEO in 2018 and has yet to deploy its sail.

These devices are an attractive option for small satellites since they can be fitted to the host satellite at a late stage in the design. Building on the success of the preceding qualified sails, Cranfield is developing a third sail: the hybrid concept (see Fig. 3). This design aims to improve the sail's scalability, adaptability and manufacturability, allowing it to be tailored to a wider range of satellite configurations. This modular design does not require a full side panel for mounting purposes and therefore, protruding hardware, such as antennas, can be accommodated without impeding sail deployment.

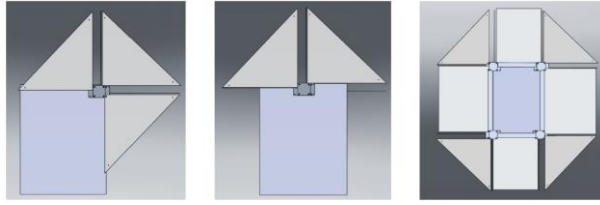


Fig. 3. Proposed Hybrid Concept

Cranfield University will be commercialising the DAS family, enabling manufacturers and operators of small satellites to comply with space debris mitigation guidelines at a low cost and low design impact. The work described in this paper will de-risk the commercialisation of the DAS product family, including raising the technology readiness level (TRL) of the hybrid concept. The following sections will detail the complementary on-going projects at Cranfield University as part of the full implementation roadmap of the DAS.

1.2 Long-Term Degradation of Aluminised Kapton in LEO

One of the key areas of research for this project is the long-term degradation of materials in LEO. LEO is a harsh environment which can cause considerable damage to spacecraft. In particular, polymeric spacecraft materials can be significantly eroded as a result of exposure to the most prevalent atmospheric species in LEO; atomic oxygen. The high flux and high reactivity of atomic oxygen readily oxidises polymers [7]. Protective coatings have been developed to protect polymeric materials and increase their resistance to atomic oxygen degradation, but microscopic defects in the coatings, as a result of fabrication and handling or due to debris and micrometeoroid impacts, can lead to the oxidation of the vulnerable underlying materials. Atomic oxygen undercutting at pin-hole voids can lead to significant erosion of the underlying polymer and could potentially cause further damage to the protective coating, eventually resulting in structural failures.

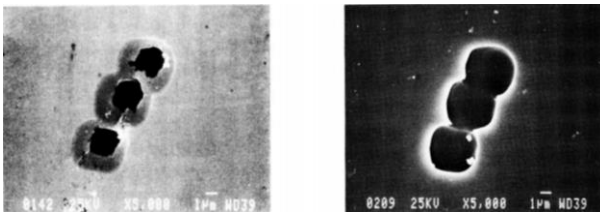


Fig. 4. Aluminised Kapton MLI sample exposed to 5.77×10^{21} atoms/cm² atomic oxygen fluence; undercutting shown with (left) and without (right) aluminium coating

The primary material of Cranfield's DAS is 25 μm vapour-deposited double-aluminised Kapton, with the aluminium coating accounting for 1 μm on either side of the Kapton. The coated polyimide film is susceptible to

the undercutting-tearing propagation mechanism and this phenomenon was first studied on-board the Long Duration Exposure Facility (LDEF) [8]. A similar sample of aluminised Kapton multilayer insulation (MLI) was located on the leading edge of the LDEF and allowed for the observation of atomic oxygen undercutting over 5.8 years. Cracks around the venting holes, included in the MLI design, provided opportune conditions to study the undercutting process. Experimentally observed results from the LDEF study were compared to Monte Carlo models, based on ground tests, predicting the undercutting profiles at defect sites. The degree of undercutting, displayed in Fig. 4, was extensive compared to models.

The experiment provided evidence of the complex interactions between the atomic fluence environment and the spacecraft. Incoming ram atomic oxygen will have transverse velocity components due to thermal and orbital inclination contributions and the scattering of unreactive atoms. Kapton has a low probability of initial reaction (approximately 14%) but unreacted atomic oxygen can scatter after penetrating the protective coating where it will have multiple opportunities to react, causing undercutting. Undercut profiles varied depending on the size and orientation of the initial defect, but generally exceeded the defect width by a factor of 2.5 to 16.6. Crucially, this study highlighted the devastating long-term effects of atomic oxygen on aluminised polyimides.

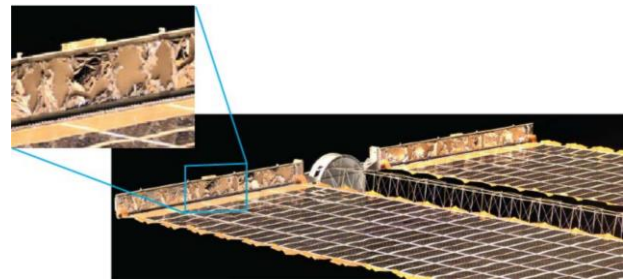


Fig. 5. Atomic Oxygen Undercutting Degradation of Aluminised Kapton Blanket after one year on the ISS

An aluminised Kapton blanket protected the ISS photovoltaic arrays prior to deployment [9]. The 24.5 μm thick double-aluminised Kapton was directly comparable to Cranfield University's sail material, albeit with a thinner 0.1 μm coating of vacuum-deposited aluminium on both sides of the Kapton. Since the 0.1 μm sputtered aluminium coating was not fully continuous, atomic pinholes were present and improved results should be expected from the DAS sail material. The aluminised Kapton blanket was exposed to LEO from December 2000 to December 2001. Photographs of the array in orbit can be seen in Fig. 5, showing the atomic oxygen undercutting degradation of the wing blanket box cover after a year of exposure. The primary

cause of the extensive degradation was atomic oxygen becoming trapped between the two aluminised surfaces. Atomic oxygen enters the aluminised layer through microscopic defects and undercutting leads to the erosion of Kapton. If the undercutting is widespread and extends through the Kapton to the bottom aluminised surface, the atomic oxygen becomes trapped and has multiple opportunities to react until it recombines, reacts or penetrates the aluminium again. A visualisation of this phenomenon can be seen in the diagram in Fig. 6. Eventually, the Kapton is fully eroded and only the thin film of aluminium remains, which is very susceptible to stress wrinkles and tears.

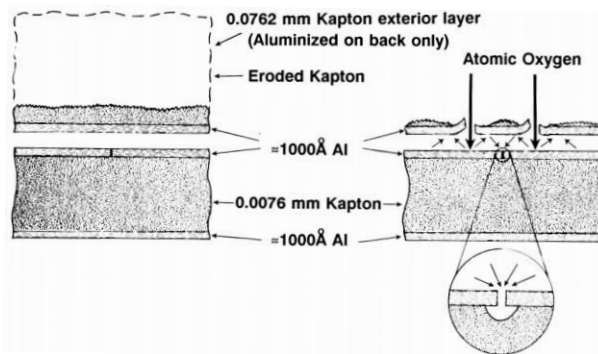


Fig. 6. Trapped atomic oxygen between MLI and exterior aluminised Kapton layer on ISS wing box [8]

Post-analysis of this case study highlighted the extent of atomic oxygen undercutting in relatively short timeframes and provided details of how coating selection and application can result in widely varying protection. Banks and Demko [7] suggested that a single top surface aluminium coating would yield improved atomic oxygen durability compared to double-aluminised Kapton. This cannot be incorporated into sail applications, but it does emphasise the severity of the damage caused by trapped atomic oxygen.

These examples on-board the ISS highlighted the rapid degradation of aluminised Kapton in a low orbit with a high atomic oxygen fluence. Despite the poor degradation characteristics associated with Kapton, it is still an attractive choice for drag sails. As aforementioned, aluminised Kapton has significant space heritage, it is commercially available, inexpensive and has excellent thermal properties. Additionally, drag sail are utilised at higher altitudes than the ISS (~600 km - 800 km) with lower atomic oxygen fluence and less severe erosion rates. Cranfield University's deployed Icarus-1 sail (deployed in November 2018) is continuing to de-orbit its host satellite at the predicted rate, not showing any signs of significant damage to the sail material. The target market for Cranfield University's drag sails is small satellites. Therefore, the cost of the drag sail and, in this case, the cost of the sail material itself is a key design driver in most cases,

making the inexpensive, off-the-shelf, reliably available Kapton an ideal choice. Other institutions, including ESA, have consistently chosen to fabricate their sails from aluminised polyimide films.

Atomic oxygen fluence will also depend on the orientation of the spacecraft and the solar activity at the time of flight. The erosion yield of aluminised Kapton, representing a material's reaction to atomic oxygen, is not sufficiently documented for long-term exposure to LEO. Base figures are available from literature, but they do not take into account external factors, such as micrometeoroid and debris impacts, or operational factors, such as a tumbling satellite. Atomic oxygen undercutting and other material processes specific to the long-term erosion of coated thin-film polyimides are not sufficiently documented in literature. Although the material has been flown to space many times previously, there is still a lack of publicly available information regarding the long-term degradation of aluminised Kapton. Aluminised Kapton samples were flown on several Material International Space Station Experiment (MISSE) missions on the ISS, but the data is only available through the Materials and Processes Technical Information System (MAPTIS); an online database reserved for NASA associated contractors and organisations. Therefore, further experimentation, and broad dissemination of results, is needed to qualify aluminised Kapton for the specific application of drag sails in LEO.

2. Drag Sail Development Testing Campaigns

The most effective means of characterising the long-term impact of the space environment on materials is through actual testing in space [10]. Although ground-based facilities have carried out tests to quantify the atomic oxygen undercutting effect, these facilities do not always accurately simulate the combined environmental effects and tend to investigate the problem in isolation, and previous test results are largely proprietary. Data published in the public domain often have conflicting results regarding the severity of long-term degradation in LEO since degradation rates depend on several factors. Altering the material's fabrication method, its application, the attitude and orientation of the spacecraft, and the atomic oxygen fluence at the time of flight (dependant on solar activity) can all have a significant impact on sail material erosion. However, opportunities to send material to space are limited, costly and time intensive. Thus, this team is proposing to carry out a preliminary testing campaign on-ground at Cranfield University, utilise those results to refine a proposed on-orbit experiment and consolidate results to improve on-ground testing facilities and methodologies, and add to the publicly available material science database.

2.1 Preliminary Sail Material Testing Campaign

Complementary to the actual testing in LEO, an accelerated ageing testing in simulated lab environment is being considered as a promising alternative to rapidly investigate the degradation of aluminised Kapton drag-sail. The team considers exposure to O₂ plasma in low vacuum, which is about six orders of magnitude higher than the pressure in LEO, to be the quickest and simplest means for understanding the degradation mechanisms by oxidation in absence of UV radiation and thermal cycling. Preliminary experiments will be carried out on commercially available 25µm vacuum deposited aluminium Kapton HN samples with and without perforation using unaluminized bare Kapton as control. These samples will be exposed to various dosages of O₂ plasma through stringent control of plasma availability, density, and residence time by systematic manipulation of the input gas flow rate, the RF plasma generator power, and exposure time. The effect of sample orientation will also be studied by placing these samples in parallel, perpendicular, or different impingement angles with respect to the plasma flows. Additional tests using off-the-shelf aluminised Kapton with an additional coating of ~100nm of oxygen saturated amorphous aluminium oxide layers will also be pursued to assess the viability of protective coatings for improvement of oxidation resistance.

It is important to note that O₂ plasma systems do not produce atomic oxygen, but instead generate a high concentration of reactive oxygen species such as ozone, superoxide radicals, triplet/singlet oxygen, peroxides, and hydroxyl ions with much shorter mean free paths [11]. In addition, the absence of a strong UV radiation and thermal cycling eliminates the need to deconvolute the compounding degradation mechanisms introduced by photodissociation of carbon-based materials, including Kapton, and thermo-mechanical fatigue at the aluminium-Kapton interfaces. The oxidation kinetics under O₂ plasma exposure may be considerably different than those under atomic oxygen exposure due to the differences in their effective masses, charges, collision densities, and impact velocities. Nonetheless, these reactive oxygen species are known to be highly reactive to carbon-based materials and can rapidly introduce degradation through modification in compositional, morphological, and microstructural features. UV radiation and thermal cycling can be introduced at a later stage once the degradation mechanisms by oxidation has been fully understood.

The effect of oxidation on aluminised Kapton will be holistically evaluated by electron microscopy, x-ray spectroscopy, and optical spectroscopy characterisations. Cross-sectional imaging will be collected to elucidate the dosage-dependent degradation through morphological and microstructural modifications near the aluminium-Kapton interfaces and to assess if the perforation intentionally introduced to

aid safe depressurisation of sail accelerates the undercutting and erosion effects. X-ray spectroscopy and optical spectroscopy, such as Raman and infrared spectroscopy, will be utilised to quantify any changes in interfacial energy and chemical compositions of the Kapton and the aluminium layer.

2.2 In-Orbit Testing

Cranfield University and Belstead Research Ltd. previously submitted a joint proposal to the ESA and CNES Euro Material Ageing opportunity. The proposal aimed to investigate the long-term degradation of aluminised Kapton drag-sail material by sending samples to the International Space Station (ISS) on-board the Euro Material Ageing facility (see Fig. 7). Although this proposal was not successful, the sample designs and testing methodologies may be applied to future alternative opportunities currently being investigated.

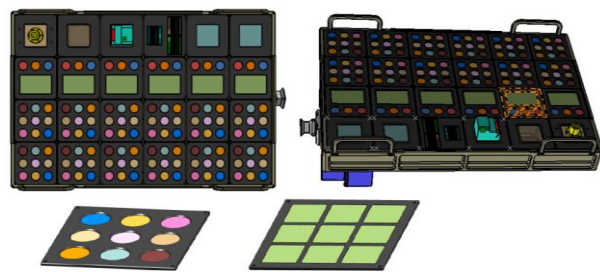


Fig. 7. Euro Material Ageing module to go on the Bartolomeo platform on-board the ISS [12]

In-orbit testing will be a valuable opportunity to determine the cumulative effects of UV radiation, thermal cycling, atomic oxygen, and micrometeoroid and debris impacts, essential to the overall assessment of the degradation process. The expected atomic oxygen fluence in the ram direction at ISS altitude for a year is roughly equivalent to those for a 15-year tumbling de-orbit for the drag sails. Preliminary experiments will be carried out at Cranfield University to fully characterise the current 25 µm sail material and estimate the degradation expected during the 6-12 month testing period. These results will be combined with analysis on the environment, such as calculating the micrometeoroid flux at ISS altitude, and will be applied to the design of in-house fabricated material samples. Based on results of the preliminary test campaign, one sample will be modified to have an increased resistance to atomic oxygen damage. Additionally, the team will investigate whether perforations in the sail, included to aid in safe depressurisation at launch and to stop tear propagation, negatively impact atomic oxygen undercutting and/or accelerate the erosion process. The sail is expected to survive long-term in LEO, accumulating defects from debris and micrometeoroid

impacts, and therefore this information will be valuable to the general understanding of long-term degradation of materials in LEO.

Four 20 mm diameter circular disk samples (ALKA01, ALKA02, ALKA03 and ALKA04) have been proposed for the experiment. ALKA01 consists of commercially the readily available 25 μ m vacuum deposited aluminium (VDA) Kapton HN, sample ALKA02 is the same material, but modified to include perforations and sample ALKA04 is similar to ALKA02, but with a false backing. Sample ALKA03 will also be fabricated using off-the-shelf aluminised Kapton with an additional coating of <100 nm of oxygen-saturated amorphous aluminium or silicon oxide layers to improve its atomic oxygen resistance.

This experiment will be a good indicator as to whether or not the sail is sufficiently durable to remain effective for the duration of the de-orbit period and will aid in ameliorating the knowledge gap in literature regarding the long-term sustainability of this widely used material. Furthermore, the team will be quantifying the effects of intentional perforations, included in the design, and unintended perforations, due to micrometeoroid and debris impacts, on the material degradation process. The results from this proposal will build on previous space-based experiments, aiding in validating the findings from previous ground-based studies and thus contribute to the overall understanding of the degradation process. The team intends to publish these results and make them available to the wider space community for future reference.

In-orbit testing does come with limitations. For most technology demonstration missions, the samples would not be actively monitored and generally only one side of the sail would be exposed to the environment. Sample ALKA04 has been included to simulate a more realistic scenario where atomic oxygen is allowed to pass through the sample, but even this setup would not be fully representative of actual in-orbit conditions. Therefore, utilising the in-orbit results to validate the findings from the preliminary ground-based testing campaign will allow the team to conduct further testing at Cranfield University where samples could be actively monitored, aiding in the characterisation of the material and better understanding the rate and sequence of events of the degradation process.

2.3 Complementary Testing and Analysis

The on-ground and in-orbit testing of the drag sail material are part of the broader roadmap for commercialising the DAS. The team is currently focused on the verification of three key areas highlighted during the CleanSat study; environmental durability, performance and mass-to-area ratio.

2.3.1 Environmental Durability

Several CleanSat environmental requirements necessitate the drag sail achieves its expected performance under the LEO environment observed during a worst-case de-orbit scenario of re-entry within 25 years. Of particular concern is the durability of the aluminised Kapton sails. As part of on-going investigations at Cranfield University, the durability of the current aluminised Kapton drag sail material will be characterised and tested, in addition to preparing samples for an in-orbit experiment.

Cranfield University will be conducting preliminary testing, including a detailed characterisation of the sail material and an analysis of the atomic oxygen erosion process, as discussed in the previous sections. This work will either qualify the current sail material, confirming it is sufficiently durable for the mission duration, or it will quantify the issue and highlight the need for a new material. The experiments will observe and characterise the degradation of the sail material due to long-term exposure in LEO, in particular the atomic oxygen undercutting phenomenon. These results and the on-orbit results will address the knowledge gap in literature and, in turn, aid in the commercialisation process by demonstrating the proven effectiveness of the material.

2.3.2 Performance

In March 2019, Cranfield University and Belstead Research Ltd. completed a UK Space Agency (UKSA) National Space Technology Programme (NSTP) Pathfinder Project investigating the deployment dynamics and demisability of Cranfield University's drag sails. The SAMj toolkit, developed by Belstead Research Ltd., was used within this Pathfinder activity to assess the dynamic behaviour of the TechDemoSat-1 (see Fig. 8) and Carbonite-1 satellites. This demonstrated the applicability of the toolset in assessing the impact of drag sail deployment on the power, attitude control system and scientific capabilities of a mission. It is proposed to enhance the SAMj toolkit to be a sales analysis tool for Cranfield University, illustrating the impact of partial or full drag sail deployment on the ability of a platform to generate scientific results. It will also be able to model the staggered deployment of several sails as part of the hybrid concept.

In order to fulfil this role, the existing SAMj vehicle visualisation tool (see Fig. 9) will need to be enhanced to add the ability to define line-of-sight cones for instruments. This will allow system engineers to assess the impact of sail deployment on system performance when placing drag sail components. The mission performance analyses completed in the previous Pathfinder activity will also be automated, allowing such data to be generated by engineers who are not SAMj specialists. Finally, the resulting tool will be packaged and deployed at Cranfield University who will

then use it to integrate a modular sail onto a canonical vehicle. The toolkit will aid in the planned market analysis performed at Cranfield University, reassuring potential customers of the capability of the sails and allowing Cranfield to assess the scope of the performance of the sails.

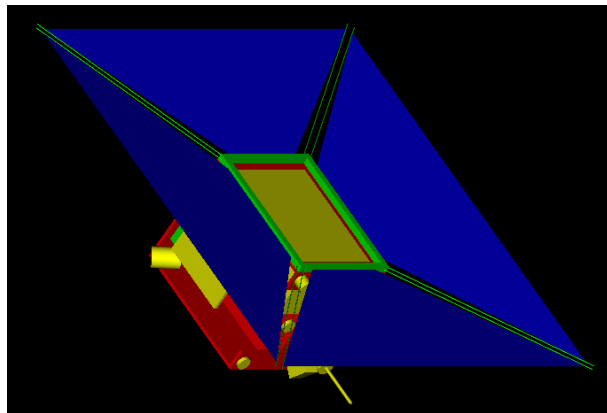


Fig. 8. TechDemoSat-1 with Deployed Sail Model

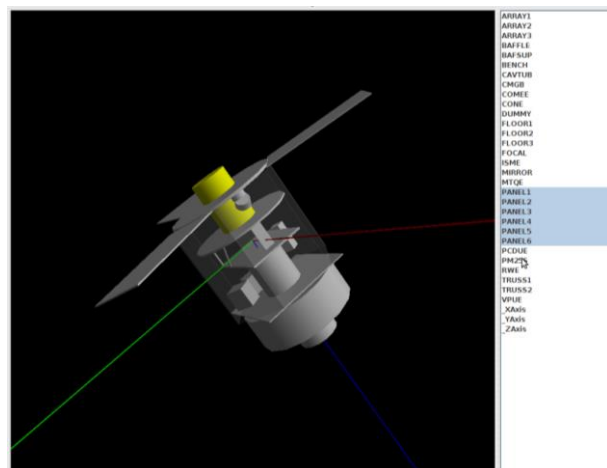


Fig. 9. Belstead Research Ltd. SAMj Toolkit

Additionally, Cranfield University will be working with Etamax to carry out a space debris and micrometeoroid risk assessment study. ESABASE2 will be used to quantify the probability of collisions between the deployed drag sail and orbital debris, and to study the effects of any space impacts. With the software it will be possible to determine whether the deployed sail is sufficiently durable to withstand the LEO environment for the required worst-case de-orbit scenario and it will aid in identifying weaknesses in the design. The ESABASE2/Debris software does not only take into account the probability of impact, but also the damage obtained from the impacts based on the spacecraft materials and damage assessment equations. Verifying the sail will be able to perform as expected during a worst-case de-orbit from 800 km (25 year re-

entry time) will assure potential customers of the reliability of the drag sail.

3.3 Mass-to-Area Ratio

To ensure a minimal impact on the host satellite, Cranfield University aims to have a deployed surface area to subsystem mass ratio better than 2.5 m²/kg, a requirement identified during the CleanSat study. Due to the booms being significantly heavier than the sail material, initially, as the size of the sails increases, the booms are still the biggest contributor to the overall mass. Currently, the length of the DOM booms is limited due to the size of the available facilities at Cranfield. Possible alternative facilities, able to accommodate the heat treatment of longer copper beryllium booms, are being investigated, as well as commercial suppliers, to develop a new production capability.

A previous scalability study of the current DOM module (and therefore, in part, the hybrid concept) highlighted that the size of the booms increases disproportionately to their mass. For larger sail areas, the current copper beryllium booms may not be able to conform to the mass-to-area ratio requirements. The output of this study was the theoretical optimal design of a composite boom for the DOM, taking into account the current DOM housing, the material type, the laminate cross-section, the layup and orientation of plies, and the manufacturing process. Cranfield has significant expertise in composites within its Enhanced Composites and Structures Centre, and will produce a prototype of this boom design and compare its performance to the copper beryllium booms.

The Low Earth Orbit negligible impact Drag Augmentation System (LEOniDAS) team from Cranfield University are currently taking part in ESA's Fly Your Thesis! programme. As part of the programme, the students will have a series of parabolic flights in October 2021 to assess the deployment of the sails in microgravity. In preparation for these flights, both the significantly longer copper beryllium booms and the previously designed composite booms will be manufactured and tested.

3. Validating Orbit Propagation Software and Atmospheric Models

The previous UKSA Pathfinder project highlighted the dependence of end-of-life analysis on the choice of atmospheric models and the simulated level of solar activity. Solar flux in particular has a significant effect on the de-orbit period. A previous study conducted at Cranfield University involved using STELA and DRAMA end-of-life analysis tools to assess the applicability of drag augmentation systems to enable future LEO spacecraft compliance with debris mitigation guidelines [13]. Similarly, this study

simulated multiple de-orbit scenarios with varied and mean solar flux conditions which yielded drastically different re-entry times (see Fig. 10).

Icarus-1 and Icarus-3 deployed approximately 22 and 29 months ago respectively (at time of writing). Preliminary analysis of the Icarus-3 deployment revealed an approximate doubling in the change in mean motion of the satellite, in line with the expected doubling of Carbonite-1's effective area from 0.6 m² to 1.25 m². This was further corroborated by Cranfield University's analysis of the publicly available two-line element set (TLE) data. Since there is now 1-2 years of Carbonite-1 and TechDemoSat-1 orbital decay data, the previous STELA and DRAMA end-of-life analysis can be updated for these two satellites. This will allow the team to compare the simulations, and more importantly the choice in atmospheric models and solar flux conditions, with actual data. Similarly to Vallado and Finkleman [14], the primary objective will be to consolidate information on the different simulation models, quantify the effects of varying certain parameters and create a framework for future analysis.

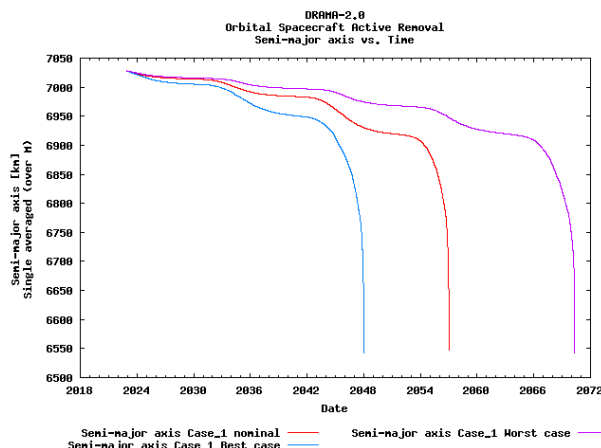


Fig. 10. Previous STELA Study: Semi-major Axis Decay vs. Time (Varying Solar Flux) [13]

The results from the analysis will be beneficial in verifying that the drag sails will ensure compliance with space debris guidelines and in updating Space Surveillance and Tracking (SST) algorithms. Ideally, if the effect of a deployed sail could be quantified, SST predictive calculations could be updated to reflect the addition of a drag sail to a satellite's end-of-life operations.

4. Conclusion

This paper highlighted the on-going research at Cranfield University in preparation for commercialising the DAS family.

Most of the primary risks of the drag sail designs are related to their lifetime and long-term exposure to the

LEO environment. These risks will be mitigated through assessing the durability of the current sail material by performing preliminary analysis at Cranfield University and validating the results with in-orbit testing. Additionally, an ESABASE2 risk assessment will study the effects of space debris and micrometeoroid impacts over the de-orbit period and establish whether the drag sails are sufficiently robust.

Following the mitigation of risks, the next step will be to address the limitations of the current design. As part of the ESA Fly Your Thesis! programme, the team will also be prototyping more scalable and lightweight booms. The project will include the fabrication of significantly longer copper beryllium booms and new composite booms in addition to assessing the deployment dynamics of the sails in microgravity.

Continuing the work from a previous Pathfinder project, the SAMj toolkit will be improved to show the impact of partial, full and staggered sail deployment. Comparing actual in-orbit data from the Icarus-1 and Icarus-3 sails to simulations will allow for validation of end-of-life analysis models and will result in a framework for future analysis, improving customer confidence.

Throughout these projects, emphasis will be placed on documenting and disseminating key findings and methodologies in order to contribute to a broader framework for assessing material degradation in LEO and end-of-life operations.

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Highlights

- Drag augmentation systems for end-of-life de-orbit of satellites
- Low-cost, simple solutions for future space debris mitigation
- Long-term degradation of aluminised Kapton in low Earth orbit
- Testing campaigns characterising material, investigating atomic oxygen erosion
- Assessment of the drag sail environmental durability, performance and scalability

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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